

REDUCING DISCOMFORT CAUSED BY ELECTRICAL STIMULATION

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority under 35 U.S.C. § 119 (e) from U.S. provisional application Serial Number 60/452,477, filed on March 7, 2003, entitled “Device, Method, and System for the Reduction of Discomfort Associated with and Facilitating Treatment via Magnetic Stimulation,” which is herein incorporated by reference in its entirety.

FIELD OF THE INVENTION

[0002] The invention relates to the field of electrical stimulation. Specifically, the invention relates to reducing discomfort created by electrical stimulation.

BACKGROUND OF THE INVENTION

[0003] A number of medical ailments are treated or treatable through the application of electrical stimulation to an afflicted portion of a patient's body. Two examples of electrical stimulation may include magnetic or inductive stimulation which may make use of a changing magnetic field, and electric or capacitive stimulation in which an electric field may be applied to the tissue. Neurons, muscle and tissue cells are all forms of biological circuitry capable of carrying electrical signals and responding to electrical stimuli. For example, when an electrical conductor is passed through a magnetic field, an electric field is induced causing current to flow in the conductor. Because various parts of the body also act as a conductor, when a changing magnetic field is applied to the portion of the body, an electric field is created causing current to flow. In the context of biological tissue, for example, the resultant flow of electric current stimulates the tissue by causing neurons in the tissue to depolarize. Also, in the context of muscles, for example, muscles associated with the stimulated neurons contract. In essence, the flow of electrical current allows the body to simulate typical and often desired chemical reactions.

[0004] Electrical stimulation has many beneficial and therapeutic biological effects. For example, the use of magnetic stimulation is effective in rehabilitating injured or paralyzed muscle groups. Another area in which magnetic stimulation is proving effective is treatment of the spine. The spinal cord is difficult to access directly because vertebrae surround it. Magnetic stimulation may be used to block the transmission of pain via nerves in the back (*e.g.*, those responsible for lower back pain). Further, unlike the other medical processes that stimulate the body, electrical stimulation may be non-invasive. For example, using magnetic fields to generate current in the body produces stimulation by passing the magnetic field through the skin of a patient.

[0005] Magnetic stimulation also has proven effective in stimulating regions of the brain, which is composed predominantly of neurological tissue. One area of particular therapeutic interest is the treatment of neuropsychiatric disorders. It is believed that more than 28 million people in the United States alone suffer from some type of neuropsychiatric disorder. These include specific conditions such as depression, schizophrenia, mania, obsessive-compulsive disorder, panic disorders, just to name a few. One particular condition, depression, is often referred to as the “common cold” of psychiatric disorders, believed to affect 19 million people in the United States alone, and possibly 340 million people worldwide. Modern medicine offers depression patients a number of treatment options, including several classes of anti-depressant medications like selective serotonin reuptake inhibitors (SSRI), MAIs, tricyclics, lithium, and electroconvulsive therapy (ECT). Yet many patients remain without satisfactory relief from the symptoms of depression. To date, ECT remains the “gold standard” of treatments for severe depression; however, many patients will not undergo the procedure because of its severe side effects.

[0006] Recently, repetitive transcranial magnetic stimulation (rTMS) has been shown to have significant anti-depressant effects for patients, even those that do not respond to the traditional methods and medications. In one embodiment of rTMS, a subconvulsive stimulation is applied to the prefrontal cortex in a repetitive manner, causing a depolarization of cortical neuron membranes. The membranes are depolarized by the induction of small electric fields, usually in excess of 1 volt per centimeter (V/cm). These small electric fields result from a rapidly changing magnetic field applied non-invasively.

[0007] It is now well known to those skilled in the art that both the left and right prefrontal cortex regions of the brain have strong communication links to Limbic System structures, which contain the “circuits” controlling mood and general behavior. One objective of rTMS is to provide stimulation to these biological circuits through a non-invasive, sub-

convulsive technique to relieve the symptoms of depression without many of the negative side effects of ECT or medications. However, one reported side effect of rTMS for the treatment of depression is patient discomfort at the site of the stimulation. This discomfort is caused, in part, by the depolarization of neuron membranes in the scalp and the resulting scalp muscle contractions that occur at the frequency of the rTMS. Testing has shown that approximately 25% of rTMS patients report this discomfort to be at a level that is very uncomfortable. In general, the greater the power and the higher the frequency of the therapeutic magnetic stimulation, the more discomfort is reported. Yet, reducing the power levels may not be a viable option because greater power has been shown to desirably stimulate deeper structures. Also, relatively higher frequencies (*e.g.*, greater than 1 Hertz (Hz)) have been shown to have a greater anti-depressant effect.

[0008] Therefore, it is desirable to develop techniques for reducing discomfort caused by electrical stimulation.

SUMMARY OF THE INVENTION

[0009] The invention is directed to a novel method for reducing discomfort caused by transcutaneous stimulation. The novel method includes providing transcutaneous stimulation, reducing the transcutaneous stimulation at a first location, and substantially maintaining the transcutaneous stimulation at a second location. The transcutaneous stimulation may be created by electric and/or magnetic fields. The first location may be relatively proximate to the cutaneous surface and may comprise tissue, nerves and muscle. Also, the second location may be relatively deeper than the first location and include, for example, brain tissue that requires the transcutaneous stimulation for treatment purposes. The invention further may include locating a conductor on a treatment area and/or a transcutaneous stimulation device relative to the first location. In addition, the method may further include adjusting how much the transcutaneous stimulation is reduced at the first location. Such adjusting of the transcutaneous stimulation may be accomplished by applying a signal at the first location. The signal may be inversely proportional to another signal used to create the transcutaneous stimulation.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] Figure 1 is a block diagram illustrating a technique for reducing discomfort caused by transcutaneous stimulation;

[0011] Figure 2 is a block diagram illustrating another technique for reducing discomfort caused by transcutaneous stimulation;

[0012] Figure 2A is a block diagram illustrating another technique for reducing discomfort caused by transcutaneous stimulation;

[0013] Figure 3 is a block diagram illustrating another technique for reducing discomfort caused by transcutaneous stimulation;

[0014] Figure 4 is a block diagram illustrating another technique for reducing discomfort caused by transcutaneous stimulation;

[0015] Figure 5 is a block diagram illustrating another technique for reducing discomfort caused by transcutaneous stimulation;

[0016] Figure 6 is a block diagram illustrating another technique for reducing discomfort caused by transcutaneous stimulation;

[0017] Figure 7 is a block diagram illustrating another technique for reducing discomfort caused by transcutaneous stimulation;

[0018] Figure 8 is a block diagram illustrating another technique for reducing discomfort caused by transcutaneous stimulation;

[0019] Figure 9 is a flow diagram illustrating a technique for treating a patient using transcutaneous stimulation;

[0020] Figure 10 is a flow diagram illustrating a technique for treating a patient using transcutaneous stimulation;

[0021] Figures 11-18 illustrate additional possible conductor configurations for reducing discomfort caused by transcutaneous stimulation;

[0022] Figure 19 provides an example of another possible conductor configuration for reducing discomfort caused by transcutaneous stimulation;

[0023] Figures 20 and 21 illustrate an example configuration for the placement of two conductors for reducing discomfort caused by transcutaneous stimulation;

[0024] Figure 22 graphically depicts the comparison of the electric field created by a magnetic core device both with and without cancellation by the placement of two conductors for reducing discomfort caused by transcutaneous stimulation; and

[0025] Figures 23 and 24 illustrate an embodiment with six conductors used to reduce the fields created by a magnetic core device for reducing discomfort caused by transcutaneous stimulation.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

Overview

[0026] In 1831, Michael Faraday discovered that the magnitude of an electric field induced on a conductor is proportional to the rate of change of magnetic flux density that cuts across the conductor. Faraday's law, well known to those skilled in the art may be represented as $E \sim -(dB/dt)$, where E is the induced electric field in volts/meter, dB/dt is the time rate of change of magnetic flux density in Tesla/second. In other words, the amount of electric field induced in an object like a conductor is determined by two factors: the magnetic flux density and the time rate of change of the flux density. The greater the flux density and its derivative, the greater the induced electric field and resulting current density. Because the magnetic flux density decreases in strength as the square of the distance from the source of the magnetic field, the flux density is greater the closer the conductor is to the source of the magnetic field. When the conductor is a coil, the current induced in the coil by the electric field may be increased in proportion to the number of turns of the coil.

[0027] When the electric field is induced in a conductor, the electric field creates a corresponding current flow in the conductor. The current flow is in the same direction of the electric field vector at a given point. The peak electric field occurs when dB/dt is the greatest and diminishes at other times. If the electric field decreases, for example after a magnetic pulse, the current flows in a direction that tends to preserve the electric field (*i.e.*, Lenz's Law).

[0028] In the context of electrical stimulation of the anatomy, certain parts of the anatomy (*e.g.*, nerves, tissue, muscle, brain) act as a conductor and carry electric current when an electric field is presented. The electric field may be presented to these parts of the anatomy transcutaneously by applying a time varying (*e.g.*, pulsed) magnetic field to the portion of the body. For example, in the context of TMS, a time-varying magnetic field may be applied across the skull to create an electric field in the brain tissue, which produces a current. If the induced current is of sufficient density, neuron membrane potential may be reduced to the extent that the membrane sodium channels open and an action potential response is created. An impulse of current is then propagated along the axon membrane which transmits information to other neurons via modulation of neurotransmitters. Such magnetic stimulation has been shown to acutely affect glucose metabolism and local blood flow in cortical tissue. In the case of major depressive disorder, neurotransmitter dysregulation and abnormal glucose metabolism in the prefrontal cortex and the connected limbic structures may be a likely pathophysiology. Repeated application of magnetic stimulation to the prefrontal cortex may produce chronic changes in neurotransmitter concentrations and metabolism so that depression is alleviated.

Systems and Methods of Reducing Discomfort

[0029] Figure 1 is a block diagram illustrating a technique for reducing discomfort caused by electrical stimulation. As shown in Figure 1, a system 100 includes a magnet stimulation circuit 101. Magnet stimulation circuit 101 is an electric circuit that provides a power signal to a main magnet (not shown). The power signal may be any time-varying electric signal capable of generating an electric and/or magnetic field. The main magnet may be used to conduct transcranial magnetic stimulation (TMS) and/or repetitive transcranial magnetic stimulation (rTMS) as described in U.S. Patent Nos. 5,725,471, 6,132,361 6,086,525 and 6,425,852, and incorporated herein by reference.

[0030] In the following description, for purposes of explanation and not limitation, specific details are set forth regarding system 100 and other systems, methods and techniques for reducing discomfort caused by electric stimulation. For example, particular components, component configurations and placements, devices, techniques, *etc.* are described in detail. However, it should be appreciated that the invention is not meant to be limited to these examples. The examples, components, *etc.* are provided simply to provide an understanding of the invention. It will be apparent to one skilled in the art that the invention may be practiced in other embodiments that depart from these specific details. Detailed descriptions of well-known devices, components, techniques, *etc.* are omitted so as not to obscure the description of the invention.

[0031] System 100 includes an inductive device 102. Inductive device 102 operates to receive a current induced upon it by a wire 107 that carries a current (I) in magnet stimulation circuit 101. The current induced on inductive device 102 by wire 107 is proportional to the time derivative of the current (I) in magnet stimulation circuit 101, based on principles of electrical induction well known to those skilled in the art. Inductive device 102 may be any device that is capable of having a current induced thereon, including for example a coil of wire and/or a current transformer, well known to those skilled in the art. Inductive device 102 may be in communication with an amplifier 103. Amplifier 103 is in communication with a signal processor 104. Signal processor 104 is in communication with a series of conductors 105a-e. Conductors 105 may be small electrodes, having small cross section so as to minimize heating from induced eddy currents. Typical maximum dimension may be approximately 5 mm. The shape of the electrodes is determined by the geometry of the electric field induced in the surface tissue. When in use, the electrodes are in electrical contact with the surface tissue, typically

through a conductive gel which reduces the contact impedance to less than approximately 20 kOhms. Also, conductors 105 may be affixed to a flexible circuit pad 106.

[0032] Flexible circuit pad 106 may be made of a Mylar™, polyester, or other polymer-type material that permits the pad and thus conductors 105 to fit the contours of the treatment area on the patient and/or to fit the contours of the magnetic stimulation device (*e.g.*, magnet with ferromagnetic core). Flexible circuit pad 106 also may have an adhesive material that permits the pad, and therefore conductors 105, to be affixed to a location in which system 100 is to operate. Also, flexible circuit pad 106 may have a conductive gel that facilitates conduction of electrical energy between conductors 105 and the treatment area. The conductive gel may be covered with a removable paper or plastic seal (not shown), which when removed permits the conductive gel to come into contact with the treatment area.

[0033] Flexible circuit pad 106 may include a connector that permits components of system 100 (*e.g.*, signal processor 104) to be readily attached and disconnected therefrom. In addition, flexible circuit pad 106 may have certain insulating materials to prevent undesirable conducting of electrical energy with the patient and/or with components of system 100.

[0034] Flexible circuit pad 106 also may include electrical or physical disposal mechanisms that require a new flexible circuit pad to be used with each treatment. Alternatively, the disposal mechanism may allow a certain flexible circuit pad a certain number of times and/or be used by a certain patient. Therefore, the disposal mechanism may prohibit undesirable re-usage of the flexible circuit pad 106, and therefore facilitate sanitary usage of flexible circuit pad 106 both for an individual patient and across numerous patients.

[0035] In operation, when main stimulation circuit 101 is provided power from an external power source (not shown) to conduct proper stimulation of the patient, current (I) travels through main stimulation circuit 101. Main stimulation circuit 101 is connected to a magnetic stimulation device (*e.g.*, an electromagnet) (not shown) that creates a magnetic field or fields designed to provide treatment to a particular area on the patient. As shown in Figure 1, providing power to the magnetic stimulation device creates magnetic fields 108a-f.

[0036] As discussed in U.S. Patent Nos. 5,725,471, 6,132,361 6,086,525 and 6,425,852, incorporated herein by reference, magnetic fields 108a-f act to stimulate nerves, tissue and muscle *etc.* in the patient for treatment or therapeutic purposes. Current (I) travels through magnetic stimulation circuit 101 and onto inductive device 102 via wire 107. It should be appreciated that inductive device 102 may be located in series with and/or in parallel with main stimulation circuit 101, or in any electrical direct or indirect communication configuration.

[0037] Inductive device 102 operates to sense a current (I) provided to magnet stimulation circuit 101 by receiving an induced electrical value that is based on the current (I) that passes to the magnetic stimulation circuit 101. For example, the value received by inductive device 102 may be an induced voltage that is proportional to a change in current (\bar{I}) in amperes divided by the amount of time in which the change in current takes place. This is expressed mathematically as $E = L \, di/dt$, where E is the induced voltage, di is the change of current, dt is the amount of time in which the change in current takes place, and L represents the electrical inductive properties of the inductive device 102. In one embodiment, the induced voltage, for example, may then be provided to an amplifier 103. Amplifier 103 operates to manipulate (*e.g.*, boost) the induced voltage E as required by system 100 and by signal processor 104.

[0038] Signal processor 104 receives the amplified induced voltage signal from amplifier 103 and may operate to further manipulate the signal depending on the characteristics of system 100. For example, signal processor 104 may operate to invert a polarity of the signal from amplifier 103. In this way, the magnetic and/or electric fields created by the magnetic stimulation device are in substantially opposite polarity to the magnetic and/or electric fields created by conductors 105.

[0039] Also, signal processor 104 may operate to ensure that the timing of the fields created by magnetic stimulation device and conductors 105 are generated substantially simultaneously. In particular, because signal processor 104 receives a signal from the circuitry that powers the magnetic stimulation device, signal processor 104 may operate to “gate” or activate the signal to conductors 105 at the same time the magnetic stimulation device is gated. In this way, the fields from the magnetic stimulation device are present at substantially the same time that the fields from conductors 105 are present. Synchronizing the fields may further facilitate the ability of the fields from conductors 105 eliminating or reducing the undesirable effects of the fields from the magnetic stimulation device.

[0040] Therefore, amplifier 103 and/or signal processor 104 further facilitate the cancellation of the fields from the magnetic stimulation device and conductors 105, as desired (*e.g.*, at or near the scalp of a rTMS patient). The precise manipulation of the signal by signal processor 104 and/or amplifier 103 will depend upon many variables including the physical and electrical characteristics of system 100, of the patient and the treatment area, and of conductors 105, just to name a few. By receiving the signal from amplifier 103 and by understanding the characteristics of the other variables, signal processor 104 may be adapted to provide the proper signal timing and strength to conductors 105 so as to create the proper fields, at the proper time, in the proper location.

[0041] In just one embodiment in the context of rTMS or TMS, the stimulating magnet may be applied to a certain location on the patient's head so as to determine the minimum amount of induced current required to affect the particular patient's neurons. For example, the "test" location may be the patient's motor center as the results are easy to identify because a portion of the patient's body may move in response to the appropriate dosage. Once the proper dose is determined at the motor center, the stimulating magnet with attached flexible circuit pad 106 may be placed on the particular treatment location to affect the neurons required to treat the patient's depression.

[0042] Signal processor 104 may then provide the signal (*e.g.*, a time-varying signal) to conductors 105. Providing the signal to conductors 105 causes a current to flow in conductors 105, which in turn creates an electric field that is generated proximate to each of the conductors. This electric field may be used to offset the electric and magnetic fields created by the magnetic stimulation device that create discomfort in the patient, without adversely impacting the desired therapeutic effect of those magnetic fields. For example, in the context of rTMS or TMS, the electric and/or magnetic fields created by conductors 105 may be designed to eliminate and/or reduce the magnetic fields created by the magnetic stimulation device at the surface of the scalp that create discomfort in the patient, without reducing the efficacy of the magnetic field created by the magnetic stimulation device within the area that is desired to be treated (*e.g.*, the brain).

[0043] In order to ensure that the magnetic fields created by conductors 105 reduce the discomfort to the patient without diminishing the usefulness of the treatment, certain characteristics of system 100 may be varied. Although not meant to be exclusive such variances may include modifying the electrical characteristics (*e.g.*, conductivity) and physical characteristics (*e.g.*, surface area) of conductors 105. Signal processor 104 may be designed to scale the applied voltage signal up and/or down to a level that permits conductors 105 to reduce the discomfort caused by the magnetic stimulation device on the patient. Also, amplifier 103 may be designed to amplify the induced voltage signal up and/or down. It should be appreciated that system 100 may include any combination of varying the above-mentioned characteristics.

[0044] In addition to being dependent on the characteristics of system 100, how much and which system features vary may depend on the particular characteristics of the patient. For example, in the context of rTMS or TMS, such specific characteristics may include, but not be limited to, the shape and size of the patient's head, the amount and density of hair on the patient's head, the particular area of the cranium that is desired to be treated, *etc.*

[0045] Figure 2 is a block diagram illustrating another technique for reducing discomfort caused by electrical stimulation. As shown in Figure 2, a system 200 includes a

flexible circuit pad 106 having a number of conductors 202a-e. Flexible circuit pad 106 may have an adhesive material that permits the pad, and therefore the conductors, to be affixed to a location in which system 200 is to operate. Conductors 202 may be small electrodes, having a maximum dimension of approximately 5mm. Also, conductors may vary in their electrical characteristics (*e.g.* conductivity) and physical characteristics (*e.g.*, size and shape) depending on their placement on flexible circuit pad 106 relative to the area that is being treated on the patient. Each of conductors 202 may be in communication with one or more pickup loops 204 via one or more wires 205a-f. Also, conductors 202 may have another connection to one or more pickup loops 204 via one or more wires 206. In these instances, wire 206 may be used to create a voltage potential or voltage difference on conductors 202. Also, wire 206 may be connected to a ground potential (either separately or grounded to the patient under treatment) to create the voltage difference. The voltage potential created on each of conductors 202 creates a desired electric field. Although just one wire 206 is shown in Figure 2 for the purpose of clarity, it should be appreciated that each of conductors 202 may have a similar voltage reference connection attached thereto.

[0046] Pickup loop 204 may be any conductive material having any particular shape (*e.g.*, straight wire, looped coil, *etc.*). Also, wires 205a-f may be any conductive material capable of carrying an electrical signal from pickup loop 204 to conductors 202. Pickup loop 204 and wires 205 may be an integrated part of flexible circuit pad 106. Also, pickup loop 204 and wires 205 may be individual components independent of flexible circuit pad 106 that may be moved in various treatment locations during operation.

[0047] As discussed with reference to Figure 1, a current (I) is applied to a magnetic stimulation device (not shown) to produce a pulsed magnetic field (having a flux density B) that is designed to provide medical treatment (*e.g.*, TMS) to a patient. In operation, pickup loop 204 may be placed anywhere within or in close proximity to the pulsed magnetic field or in a similar magnetic field that is proportional to the therapeutic field. The therapeutic field induces an electric field (E_1) in the surface tissue whose lines of flux are shown as 203a-f. This electric field, E_1 , is proportional to dB/dt . The magnetic field flux lines (B) are orthogonal to these electric field lines.

[0048] The pickup loop may be connected via conductors 205 directly (or indirectly) between an electrode (202a-e) and a ground reference point or a second electrode. As the magnetic field crosses pickup loop 204, a current is generated in pickup loop 204 and a voltage may be established between the connected electrodes that is generally proportional to $-dB/dt$ and $-dI/dt$ over certain regions near the electrodes. This voltage creates a proportionate electric field

(E2) in the surface tissue between the electrodes. Since this applied electric field (E2) may be designed to be inversely proportional to the induced electric field (E1), there is subtraction wherever the fields superimpose which results in the desired reduction of discomfort.

[0049] In order to effectively distribute the canceling electric field (E2) multiple electrodes may be used. In this case, the voltage generated by pickup loop 204, which is proportional to the magnetic field created by the magnetic stimulation device, may be provided to each of conductors 202 via wires 205. As a result, voltages may be established between the several conductors 202 and creating corresponding electric fields between each of conductors 202. The electric fields created by conductors 202 are designed such that the undesired stimulation of the patient (*e.g.*, in the scalp) is reduced, but the desired stimulation (*e.g.*, in the brain) created by the magnetic stimulation device's magnetic field is not compromised. For example, in the context of transcranial magnetic stimulation, the electric fields created by conductors 202 may operate to reduce the impact of the magnetic stimulation device's magnetic field close to the surface of the scalp, while allowing the electromagnet's magnetic fields to penetrate deeper within the head and desirably stimulate the brain.

[0050] The desired strength and location of the fields created by conductors 202 may be varied depending on the characteristics of the patient and of system 200, as previously discussed. Although not exclusive of the techniques for varying the strength and location of the electric fields created by conductors 202, the electric fields may be varied by modifying the number of turns, the cross-sectional area of pickup loop 204, or by interposing an amplification device (*e.g.*, transformer) between the pickup loop and the electrodes as described by System 300, Figure 3. Another technique for varying the electric field strength created by conductors 202 includes using more than one pickup loop and varying the location of pickup loop(s) with respect to the magnetic field.

[0051] By sensing the strength of the magnetic field created by the magnetic stimulation device, pickup loop 204 may create fields (via communication with conductors 202) that are able to eliminate or reduce undesired effects of the magnetic stimulation device, while permitting the desired therapeutic effect of magnetic stimulation device (*e.g.*, TMS). The precise size and location of the fields created by conductors 202 may be determined by vectorally adding, as is well known to those skilled in the art, the corresponding fields created by conductors 202 and by the magnetic stimulation device.

[0052] Figure 2A is a block diagram illustrating another technique for reducing discomfort caused by electrical stimulation. Specifically, Figure 2A shows another configuration of pickup coils and conductor placement, as compared to that shown in Figure 2. As shown in

Figure 2A, conductors 209a-f are distributed on flexible circuit pad 106. Conductors 209 also are in communication with pickup coils 210a-d. Wires 207a-d are connected from conductor 209 to pickup coils 210a-d, respectively. Also, pickup coils 210a-d are connected to a voltage reference point (*e.g.*, ground reference) via wires 208a-d, respectively. The voltage reference may be separately provided, provided as part of the flexible circuit pad and/or be provided via attachment to the patient under treatment.

[0053] In operation, each of pickup coils 210 provides a certain predetermined voltage value to each of its respective conductors 209. The precise voltage value provided by pickup coils 210 to conductors 209 may be based on the electric and/or magnetic field that is desired to be created by each of conductors 209 to offset the undesirable effects of the magnetic stimulation device (not shown). The design of the voltage value may be made to vary depending on the size and construction of conductors 209, as well as the size and construction of pickup coils 210. For example, possible voltage values are indicated in Figure 2A. These voltage values are merely provided for the purpose of example and to provide further the explanation.

[0054] In just one embodiment, for example, pickup coil 210d may provide -2 volts to each of conductors 209e and 209f. Also, pickup coil 210c may provide -1 volt to conductor 209, while pickup coil 210b provides +1 volt to conductor 209c. Conductors 209a and 209b may each receive +2 volts from pickup coil 210a. The voltage values and the polarity of the voltage may be based on the electric and/or magnetic field that is desired to be created on each of conductors 209. For example, a higher voltage value (*e.g.*, 5 volts) may be applied to conductors 209c and 209d in recognition that greater undesirable field strengths are created by the magnetic stimulation device at that location. Also, by establishing a similar voltage but different polarity conductors may work in tandem (*e.g.*, 209a and b, 209c and d, and 209e and f) to create the desired fields.

[0055] Although not shown in Figure 2A, it should be appreciated that a voltage potential may be created individually on each of conductors 209. In particular, a voltage potential (*e.g.*, ground potential) may be created on one or more conductors 209 to generate a desired field. Also, it should be appreciated that the number of coils 210 and conductors 209 may vary depending upon the particular application.

[0056] Figure 3 is a block diagram illustrating another technique for reducing discomfort caused by electrical stimulation. As shown in Figure 3, a system 300 is similar to system 200, discussed with reference to Figure 2. In addition to the components shown in system 200, system 300 also includes a signal processor 301 in communication with pickup loop 204 via wire 302. As with signal processor 104, discussed with reference to Figure 1, signal

processor 301 may operate to manipulate the electrical voltage and/or current induced on pickup loop 204 and provided to conductors 202. In particular, depending on the characteristics of system 300, signal processor 301 may be designed to scale the induced voltage and/or current signal up and/or down to a level that permits conductors 205 to create a magnetic field sufficient to reduce the discomfort caused by the magnetic stimulation device (not shown) on the patient, without reducing its therapeutic effects.

[0057] The design and output of signal processor 301 may be used in lieu of or in combination with the modifications used to vary the electric fields created by conductors 202, as discussed with reference to Figure 2 with regard to the characteristics of pickup loop 204. An amplifier (not shown), similar to amplifier 103 discussed with reference to Figure 1 may be designed to amplify the induced voltage signal up and/or down in combination with signal processor 301. Also, system 300 may include any combination of varying the above-mentioned characteristics to allow conductors 202 to produce electric fields that have proper characteristics to reduce discomfort created by therapeutic electrical stimulation. For example, having the flexibility to vary the signal from pickup loop 204 using signal processor 301 may allow less stringent design criteria restrictions for the construction and placement of conductors 202, and thus further facilitate on-site implementation.

[0058] Also, it should be appreciated that signal processor 301 may be designed to allow different voltage and/or current signal strengths to be applied individually to each of conductors 202. This variable conductor signal may be desirable in certain configurations. For example, as shown in Figure 3, electric field lines 203a and 203d converge as they approach the center of flexible circuit pad 106. Because it is well known to those skilled in the art that field lines 203a and 203d may vectorally add in this location, resulting in a greater electric field strength (created by the magnetic stimulation device) at this location than at other locations in system 300.

[0059] In the context of rTMS and/or TMS, this greater electric field strength beneficially may result in ideal stimulation of the brain for the treatment of depression, for example. At the same time, this greater electric field strength also undesirably may result in creating greater discomfort in the non-brain tissue, muscle and/or nerves, or other parts of the brain that do not need to be stimulated. Therefore, in order to offset the undesirable effect where electric field lines 203a and 203d are stronger, signal processor 301 may apply a larger voltage and/or current signal to a conductor located in this location than to other conductors. For example, conductor 202c may receive a greater voltage and/or current signal than the other conductors because it is located in the area where electric field lines 203a and 203d are stronger.

Therefore, signal processor 301 may permit conductor 202c to create a relatively greater electric field as compared to the other conductors.

[0060] Although the discussion of the ability of signal processor 301 to vary the current and/or voltage signal provided to each of conductors 202 has been discussed in the context of field strength, this example is not exclusive. It should be appreciated that other factors may drive the decision to provide different signals to each of conductors 202. For example, the anatomy or sensitivity of the part of the patient that is being treated with respect to the arrangement of the conductors on flexible circuit pad 106 may result in signal processor 301 providing a relatively greater and/or lesser current to conductor 202a than the other conductors. Also, as another example, the lines of flux created by the main electromagnet device may be different than as illustrated in Figure 3 and thus the design of signal processor 301 may be such that greater current and/or voltage signal may be provided to other of conductors 202. Therefore, it should be appreciated that the discussion is not meant to be limited to any of the above examples, which simply are provided for the purpose of clarity and explanation.

[0061] Figure 4 is a block diagram illustrating another technique for reducing discomfort caused by electrical stimulation. As shown in Figure 4, a system 400 includes a flexible circuit pad 401 having conductors 402a-d. Although conductors 402 are shown centered and evenly spaced on flexible circuit pad 401, it should be appreciated that conductors may be any size or shape, arranged in any configuration, and placed on any location on flexible circuit pad 401. Also, although conductors 402 are illustrated as having an arc shape, it should be appreciated that the invention is not limited to any particularly shaped conductors. For example, conductors 402 may have any shape, including the shapes depicted in Figures 1-3, circular coil shapes, *etc.* Conductors 402 also are connected to a common connector 403. Common connector 403 may provide a referenced voltage level, like a ground voltage level, for example. Also, as previously discussed, the magnetic stimulation device (not shown) creates magnetic flux lines 404a-f

[0062] In operation, system 400 uses shielding techniques to reduce and/or to redistribute the electric field effects of fields 404a-f created by the magnetic stimulation device and used for therapeutic purposes (*e.g.*, rTMS and TMS). In particular, as previously discussed, magnetic flux lines 404 create electric fields which induce electrical currents in the nerves, muscle and tissue of the patient. Certain of these nerves, muscle and tissue may be desirably stimulated by the induced current (*e.g.*, the brain in rTMS and TMS). However, certain of other nerves, muscle and tissue (*e.g.*, the scalp in rTMS and TMS) may be undesirably stimulated by the induced current created by the magnetic stimulation device.

[0063] Conductors 402 operate to disrupt the flow of current in the patient's surface tissue so that system 400 may permit the desirable stimulation of certain parts of the patient's anatomy, while reducing or eliminating the undesirable stimulation of other parts of the patient. In particular, conductors 402 may be designed with certain physical and/or electrical characteristics such that they offer a path of lesser resistance for the induced current than the portion of the patient in which the undesired induced current would flow. As a result, conductors 402 operate to reduce or eliminate the undesired current induced a certain portion of the patient, while still permitting the desired current to be induced in another portion of the patient.

[0064] The characteristics of conductors 402 may be designed to provide the path of lesser resistance based upon a number of factors and variables. For example, increasing the conductivity of conductors 402 may be accomplished by varying the physical and/or electrical characteristics of conductors 402 as compared to the particular portion of the patient that is being treated. Also, the shape and configuration of conductors 402 relative to the direction and strength of magnetic fields 404a-f may be varied (*e.g.*, conductors 402 may be curved as illustrated in Figure 4) to allow conductors 402 to provide a larger conductive path of lesser resistance. In addition, conductors 402 may be configured and shaped (*e.g.*, curved) to allow the conductors to be in a substantially perpendicular arrangement with respect to electric field lines 404a-f in order to "intercept" more of the current caused by the induced electric field, conduct the intercepted current to a more acceptable location, and redistribute the current back to the surface-proximate tissue in a manner that minimizes sensation. Although determining the configuration and shape of conductors 402 may be necessary in properly reducing or eliminate the undesired induced current on the patient, it should be appreciated that the invention is not limited to any particular shape or configuration of the conductors, but include all possible shapes and configurations.

[0065] In the context of rTMS and TMS, conductors 402 may have electrical and physical characteristics to redirect the flow of current away from the tissue, nerve, and muscle found closer to the surface of the head or scalp. One way of accomplishing this may be by determining the typical or specific electrical conductivity of the surface-proximate tissue, nerve, and muscle, and designing conductors 402 to have an equal or greater conductivity, as necessary. Also, the electrical and physical characteristics of conductors 402 may be designed to redirect current that may stimulate the surface-proximate tissue, nerve, and muscle without significantly interfering with the therapeutic current desirably induced on the brain tissue under treatment.

[0066] Although conductors 402 are shown connected to common connector 403, it should be appreciated that any one or more of conductors 402 may operate independently of the

others, or that just one conductor may be used. For example, in the context of rTMS and TMS, it is well known to those skilled in the art that the trigeminal nerve is particularly sensitive to electrical stimulation as compared to other prefrontal areas of the scalp. Therefore, one or more conductors 402 may operate together or independently in close proximity to the trigeminal nerve to redirect any nearby electric fields. Also, certain conductors 402 may be dedicated to protecting the trigeminal nerve specifically. In addition, in the context of the trigeminal nerve, in just one embodiment, the conductor or conductors 402 may be positioned directly over the trigeminal nerve and attached directly to the patient in a direction consistent with the direction of the nerve. In this way, the arrangement, positioning and configuration of the conductor or conductors may be customized to locally protect a particular tissue, muscle or nerve, like the trigeminal nerve. Although the discussion has focused on protecting of the trigeminal nerve, it should be appreciated that one or more conductors may be placed over any part of the patient that may be more or less sensitive or that simply is desired to be protected. In addition, it should be appreciated that placing one or more conductors on the patient may be used in combination with any of the other techniques described with reference to Figures 1-3.

[0067] Figure 5 is a block diagram illustrating another technique for reducing discomfort caused by electrical stimulation. As shown in Figure 5, a system 500 includes conductive coils 503a and 503b located above a patient's head 502 and under a magnetic stimulation device 501 (*e.g.*, magnet with ferromagnetic core). Also, conductive coils 503a and 503b are in communication with a signal processor 506, which receives electrical power from a power source 507. Although the arrangement of magnetic stimulation device 501 and conductive coils 503a and 503b are illustrated in Figure 5 in a certain configuration with respect to the patient's head 502, it should be appreciated that this configuration is not meant to be exclusive, but simply provide one example for the purposes of clarity and explanation. For example, conductive coils 503a and 503b may be in direct or indirect contact with either the patient's head 502 and/or magnetic stimulation device 501. Furthermore, conductive coils 503a and 503b may be located other than in between the patient's head 502 and magnetic stimulation device 501. Also, although magnetic stimulation device 501 is shown as a magnet having an arc-shaped ferromagnetic core, it should be appreciated that it may include any device capable of creating magnetic stimulation.

[0068] When an electric voltage and/or current is applied to magnetic stimulation device 501, a magnetic field having magnetic flux lines 505a-d is created between the poles of magnetic stimulation device 501. The pulsed magnetic field created by magnetic stimulation device 501 and having magnetic flux lines 505a-d also create an electric field represented by

504a-e. Of course, as with Figures 1-4 the depiction of magnetic flux lines 505a-d and electric field 504a-e are merely representative of such properties simply for the purpose of a discussion in the context of the invention.

[0069] As shown in Figure 5, electric fields 504a-e become dispersed as they move away from magnetic stimulation device 501. Yet, at the top of the patient's head 502 (or perhaps in another location depending on the location and configuration of the magnetic stimulation device) located between the poles of magnetic stimulation device 501, the electric field lines 504a-e are located closer to one another. Also, well known to those skilled in the art, the strength of the electric field decreases as a square of the distance away from the source of the electric field. These two well-known properties of electric fields create a relatively stronger electric field presence at the top of the patient's head 502 and between the poles of magnetic stimulation device 501. As a result, this relatively stronger electric field in turn induces a relatively larger current in the surface-proximate tissue, muscle and nerves located at the top of the patient's head 502. In some instances, this relatively larger current may cause greater discomfort to certain portions of the patient's anatomy (*e.g.*, the scalp). System 500 uses conductive coils 503a and 503b to help alleviate the patient's discomfort.

[0070] Conductive coils 503a and 503b receive electrical power from power source 507 via signal processor 506. When conductive coils 503a and 503b receive electrical energy another magnetic field (B2, not shown) is created by conductive coils 503a and 503b. The magnetic field (B2) created by conductive coil (in cooperation with power source 507 and signal processor 506) may be designed to reduce, eliminate or counteract the magnetic lines of flux 504a-e, so as to eliminate discomfort caused by the current induced in a portion of the patient's head 502 by electric field 504a-e and magnetic lines of flux 505a-d. The location, size and strength of conductive coil's 503 magnetic field (B2) required to sufficiently offset the surface effect of the magnetic field (B) created by magnetic stimulation device 501 may vary with the particular circumstances and construction of system 500. For example, the necessary offsetting magnetic field (B2) created by conductive coils 503a and 503b may vary with the patient, the construction and location of magnetic stimulation device 501, the size and construction of conductive coils 503a and 503b, and other variable circumstances. Also, conductive coils 503a and 503b may be wound in a direction opposite of main magnetic stimulation device.

[0071] There are numerous methods and techniques available to accommodate the variation necessary in system 500 to sufficiently offset the undesirable effect of the fields created by magnetic stimulation device 501. For example, signal processor 506 may receive a feedback signal (not shown) from magnetic stimulation device 501 and/or its electric or magnetic fields so

as to create a properly sized magnetic field from conductive coils 503a and 503b. This feedback may be provided via a direct connection to magnetic stimulation device 501 or by receiving a current supplied to magnetic stimulation device 501. Using this input, signal processor 506 may vary the level of power provided to conductive coils 503a and 503b and thus vary its resulting and offsetting fields. An alternative arrangement is to permit the operator to manually adjust current levels to coils 503a and 503b based on patient feedback, based on other signal feedback, or arbitrarily.

[0072] Also, the arrangement, location and configuration of may be varied depending on the particular circumstances. For example, the number of turns or loops in conductive coils 503a and 503b may be varied based on the output of magnetic stimulation device 501. Also, as depicted in Figure 5, a plane of conductive coils 503a and 503b may be orthogonal to the magnetic field created by the magnetic stimulation device 501 and/or to magnetic stimulation device 501 itself. In addition, conductive coils 503a and 503b may be designed to have a certain cross-sectional area and/or aspect ratio.

[0073] Also, although signal processor 506 and power source 507 are shown, the size and construction of conductive coils 503a and 503b may be designed such that the desired strength of the magnetic field is created by conductive coils 503a and 503b itself. This design may be based on the electrical properties of conductive coils 503a and 503b, such as conductivity, field saturation level, influence of magnetic flux lines 504a-e on conductive coils 503a and 503b, and undesirable heat generating properties of conductive coils 503a and 503b, *etc.* The conductive coils may have air cores, or ferromagnetic cores of materials such as 3% silicon steel or vanadium permendur. These are just examples of possible materials that may be used to create conductive coils 503a and 503b.

[0074] It should be appreciated that the described techniques for arriving at the correct offsetting magnetic field created by conductive coils 503a and 503b may be accomplished via a combination of these or any other techniques. Also, it should be appreciated that the size and location of the countervailing magnetic field created by conductive coils 503a and 503b may be such that the discomfort causing effect on surface-proximate tissue, muscles and nerves are reduced, while the therapeutic effect of magnetic lines of flux 505a-d on deeper elements (*e.g.*, the brain) are not adversely effected. For example, the geometry of conductive coils 503a and 503b may be varied such that its magnetic fields do not deeply penetrate the patient (*e.g.*, air core coil). As another example, the current provided to conductive coils 503a and 503b may be minimized so as to produce relatively weaker magnetic fields.

[0075] It also should be appreciated that conductive coils 503a and 503b may be one of an array of coils. In this example, each of the coils may have similar or different physical and electrical characteristics depending upon the portion of magnetic stimulation device's 501 magnetic field that it is designed to be operated upon. In addition, each coil of such an array may have a separately adjustable current drive level that is set by the signal processor 506 based on preset values, empirically determined values, sensed feedback, patient feedback to the operator, or independent manual setting by the operator.

[0076] The coils may be attached directly or indirectly to the patient's head 502 and/or attached directly or indirectly to magnetic stimulation device 501. System 500 also may use shielding techniques to block or reduce the magnetic fields generated by conductive coils 503a and 503b from adversely effecting the operation of ferromagnetic core 501, or to minimize coupling of the stimulator field (B) with the conductive coils. For example, system 500 may include a magnetic shield (not shown) placed in some location proximate and/or between conductive coils 503a and 503b and magnetic stimulation device 501, so as to reduce or eliminate the magnetic field between conductive coils 503a and 503b and the magnetic stimulation device 501. Such magnetic shields may be fabricated from ferrite materials, as an example.

[0077] The components shown in Figure 5 are not exclusive but are provided simply for the purposes of explanation. Other components may be desirable, as well. For example, communication between conductive coils 503a and 503b may pass through a shunting device, so as to eliminate any undesirable conduction of energy back into signal processor 506.

[0078] Figure 6 is a block diagram illustrating another technique for reducing discomfort caused by electrical stimulation. As shown in Figure 6, a system 600 includes one or more ferrite pads 601 located above a patient's head 502 and under a magnetic stimulation device 501. It should be appreciated that the physical configuration of ferrite pads 601 are illustrated for the purpose of discussion and clarity, and is not meant to be an exclusive representation of such a configuration. For example, as with conductive coils 503a and 503b discussed with reference to Figure 5, ferrite pads 601 may be located between magnetic stimulation device 501 and the patient's head 502. Also, as discussed, ferrite pads 601 may be attached directly and/or indirectly to the patient's head 502 and/or directly or indirectly connected to magnetic stimulation device 501. In addition, the number and placement of ferrite pads 601 are not limited to any particular configuration, and may be used in conjunction with any of the other methods described herein.

[0079] Ferrite pads 601 operate to effectively “absorb” the magnetic field and magnetic flux lines 504a-e created by magnetic stimulation device 501. In particular, ferrite pads 601 may be designed and constructed to offset, reduce and/or absorb the magnetic flux lines 504a-e that stimulate the surface-proximate tissue, while permitting those magnetic flux lines that penetrate deeper into the patient for therapeutic purposes to pass substantially unaffected. Also, by using a ferrite material, ferrite pads 601 typically have low conductivity and therefore do not encourage induced eddy currents and associated heating or temporal disruption of the therapeutic magnetic field created by magnetic stimulation device 501. It should be appreciated that although system 600 has been described in the context of ferrite material, the pads also may be made of other non-ferrite material and/or a combination of ferrite material and non-ferrite materials.

[0080] The components shown in Figure 6 are not exclusive but are provided simply for the purposes of explanation. Other components may be desirable, as well. For example, in response to the magnetic field from the magnetic stimulation device 501, ferrite pads 601 may create fields that undesirably are directed toward magnetic stimulation device 501. Such undesirable fields may effect the operation and/or efficiency of magnetic stimulation device 501. For example, such fields may cause magnetic stimulation device 501 to saturate at a different level than expected. Therefore, other components may be used to block or attenuate the fields from ferrite pads 601 to magnetic stimulation device 501. Such blocking techniques may be designed to be unilateral or substantially unilateral to permit the fields to pass from magnetic stimulation device 501 to ferrite pads 601, but to interrupt the fields from ferrite pads to magnetic stimulation device 501.

[0081] Figure 7 is a block diagram illustrating another technique for reducing discomfort caused by electrical stimulation. As shown in Figure 7, a system 700 includes a magnetic stimulation device 702 that receives power from a stimulation circuit 703 to create magnetic fields (not shown) in the patient’s head 706. As previously discussed, magnetic stimulation device 702 creates magnetic fields that induce current within the patient for certain beneficial therapeutic effects, like the treatment of depression using TMS, for example. Also, however, the same magnetic fields create discomfort for the patient by undesirably inducing current into surface-proximate tissue, nerves and muscle.

[0082] A surface coil 701, located at or near the patient (and possibly between the patient and magnetic stimulation device 702), may be used to offset, eliminate or reduce the undesired effects of the magnetic fields created by magnetic stimulation device 702. In particular, surface coil 701 may generate its own magnetic field(s) that offset the portion of the magnetic fields created by magnetic stimulation device 702 that act to undesirably stimulate

surface-proximate tissue, nerves and muscle. Also, the values of the magnetic fields created by surface coil 701 may be such that the magnetic fields created by magnetic stimulation device 702 having therapeutic value continued to be passed to the patient without substantial interference.

[0083] The strength and timing of the magnetic fields, for example, created by surface coil 701 may be generated using a number of techniques. These techniques are similar to the example discussed with reference to Figures 1-4. Although these techniques will be discussed, it should be appreciated that these examples are provide for the purpose of clarity and further explanation, but are not meant to provide exclusive examples as contemplated by the invention.

[0084] In one embodiment, for example, power source 705 provides power to signal generator 704. Signal generator 704 then passes a signal (*e.g.*, current and/or voltage signal) to surface coil 701 to create a magnetic field from surface coil 701. The required strength and location of the magnetic field from surface coil 701 may be varied by signal generator 704 or by power source 705. Signal generator 704 also may apply the timing necessary to synchronize the firing of the fields created by surface coil 701 with the firing of the fields created by magnetic stimulation device 702. Also, the physical and electrical characteristics of surface coil 701 may be varied.

[0085] In another embodiment, for example, the operating power and timing may be provided to signal generator 704 by inducing a current from stimulator circuit 703. In this way, signal generator 704 would receive a signal indicative of the firing and value of the current provided to magnetic stimulation device 702. This current value may be translated by signal generator 704 to create the proper strength and timing for the magnetic field(s) created by surface coil 701. The current may be induced from stimulator circuit 703 using an inductive device (not shown) capable of inducing (and thus measuring) the current provided to magnetic stimulation device 702 via stimulator circuit 703.

[0086] In another embodiment, for example, surface coil 701 may operate independently of any external signal generator and power source, and simply generate its magnetic field based on the magnetic field created by magnetic stimulation device 702. Using this technique focuses on the electrical and physical characteristics of surface coil 701. In particular, surface coil 701 may be designed to react to the magnetic field created by magnetic stimulation device 702 in a way that permits therapeutic magnetic fields to penetrate the patient, while eliminating or reducing magnetic fields undesirably stimulating surface-proximate nerves, tissue and muscles.

[0087] As discussed with reference to Figures 1-4, surface coil 701 may be a part of a flexible circuit pad having an adhesive material that permits the pad to be affixed to a treatment

location. Alternatively, surface coil 701 may be affixed to magnetic stimulation device 702. Also, where more than one surface coil 701 is used, some surface coils may be attached to a flexible circuit pad, while other surface coils may be affixed to magnetic stimulation device 702.

[0088] Figure 8 is a block diagram illustrating another technique for reducing discomfort caused by electrical stimulation. As shown in Figure 8, a system 800 includes a power supply 801 in communication with electrodes 802a and 802b. Although two electrodes are shown in Figure 8, it should be appreciated that any number of electrodes may be used.

[0089] As previously discussed, magnetic stimulation device 501 creates magnetic lines of flux 505a-d, which in turn create electric fields 504a-e. Electric fields 504a-e induce both desirable and undesirable electric currents on and within the patient's head 502. System 800 overcomes the discomfort created by the undesired electric currents, while permitting the desired electric currents to continue to have their therapeutic effect on the patient. In particular, power supply 801 provides power (*i.e.*, current and/or voltage) to electrodes 802. Electrodes 802 conduct the power from power supply 801 to the patient's head 502.

[0090] The power provided to electrodes 802 may be substantially constant or time-varying. When the power is substantially constant, the power conducted to the patient's head 502 via electrodes 802 creates a substantially constant electric field in the nerves, muscle and tissues of the patient that lie in between or proximate to electrodes 802. The electric field created by electrodes 802 may have a strength that biases certain cells (*i.e.*, those that are undesirably stimulated by magnetic stimulation device 501). The bias level may be such that the cells are biased near or above their depolarization level. By biasing the cells at or near their depolarization level, electrolytes for example, are redistributed along the cell, thus reducing the ability of the electrolytes from being transported across the cell membrane. Reducing the ability of the electrolytes from being transported across the cell membrane reduces the possible stimulation of those cells by magnetic stimulation device 501, because the cells may not be as capable of repeatedly responding to the induced electric field created by magnetic stimulation device 501. As a result, the discomfort felt by the patient during treatment is reduced. Although this example was discussed in the context of a substantially constant power source, it should be appreciated that the power need not be applied throughout the entire treatment, but may for example be turned off at any point after the beginning of a pulse corresponding to the therapeutic magnetic stimulation.

[0091] In addition to, or instead of, a substantially constant power supply provided when the magnetic stimulation is applied, power provided by power source 801 may be time-varying. The time-varying signal from power source 801 may be used to desensitize the muscle,

tissue and/or nerves that undesirably are stimulated by magnetic stimulation device 501. In particular, power source 801 may be designed to pre-stimulate (*i.e.*, prior to the therapeutic pulse applied by magnetic stimulation device 501) particular nerves, muscle and/or tissue to reduce their ability to undesirably respond to the otherwise therapeutic pulse.

[0092] For example, in the context of TMS, response time constants for cortical nerves typically range from 50 to 100 microseconds, while response time constants for peripheral nerves (*e.g.*, scalp) range from 200 to 300 microseconds. Because peripheral nerves are slower to recover than the cortical nerves, stimulating the peripheral nerves just prior to application of the therapeutic magnetic stimulation reduces the peripheral nerves ability to respond to the therapeutic magnetic stimulation, and thus reduces the discomfort the patient feels as a result of the therapeutic magnetic stimulation.

[0093] Although system 800 was discussed in the context of electrodes having direct contact with the patient's head 502, it should be appreciated that system 800 also may apply electrical energy to the patient inductively, for example, using surface stimulation coils. Furthermore, while system 800 was described in the context of cortical nerves and its peripheral nerves, it should be appreciated that system 800 may apply to any circumstances where the nerves that are desired to be stimulated have an equivalent or faster response time than the nerves that are not desired to be stimulated. In addition, it should be appreciated that the required timing and frequency of the biasing or desensitizing signal provide to the patient may vary with many factors, including the characteristics of the patient and the characteristics of magnetic stimulation device 501.

[0094] System 800 also may be used in combination or independent of a drug that acts to desensitize the nerves, muscle and tissue that is undesirably stimulated by magnetic stimulation device 501. For example, a topical or injected drug may be used to desensitize or insulate the nerves, muscle and tissue from the magnetic stimulation. Such procedures may include an analgesic, anesthetic, muscle relaxant, or paralytic agent, for example. These drugs may be applied prior to the therapeutic treatment from magnetic stimulation device 501.

[0095] Figure 9 is a flow diagram illustrating a technique 900 for treating a patient using transcutaneous magnetic stimulation. As shown in Figure 9, in step 901, a magnetic field is directed to a treatment area on the patient. In step 902, a flexible circuit pad is applied to the treatment area, which may include the patient and/or magnetic stimulation device. In step 903, a conductive gel material is applied between the flexible circuit pad and the patient. In step 904, the patient is treated with the magnetic field.

[0096] Figure 10 is a flow diagram illustrating a technique 1000 for treating a patient using transcutaneous magnetic stimulation. As shown in Figure 10, in step 1001, a portion of the brain is magnetically stimulated. In step 1002, a signal is provided to the conductor and in step 1003 an electric and/or magnetic field is created by the conductor. In step 1004, the strength and location of the electric and/or magnetic field is adjusted as a function of the magnetic stimulation. In step 1005, cutaneous-proximate stimulation is reduced and/or eliminated using the electric and/or magnetic fields created by the conductor. In step 1006, the patient is treated with the magnetic stimulation. The steps of technique 1000 may be accomplished using the systems described with reference to Figures 1-8 or any other systems.

[0097] As shown in Figures 11-18, additional possible conductor configurations are shown. Again, it should be appreciated that such configurations are not meant to provide exclusive, but are meant to provide further explanatory details. The invention may include any of the configurations shown, as well as any combination of those configurations.

[0098] As discussed, placement and configuration of the conductors will be dependent on many variables, including the characteristics of the stimulation device, characteristics of the patient, and characteristics of the conductors, just to name in a few. Although the invention includes all such possible configurations, Figure 19 provides one particular example for greater clarity and explanation. In one embodiment illustrated in Figure 19, a magnetic core device may be constructed to be partially hemispherical, extend approximately 220°, and may be constructed of 3% silicone steel laminations. In this one example embodiment, the magnetic core device may be wound with eight turns of #8 American Wire Gauge (AWG) wire. The magnetic core device also may be composed of M-19 steel that saturates at 1.7 Tesla. Also, the core may be excited at 20,364 AT, RMS, which corresponds to a peak current of 3600 Amperes, delivered at 100% power. Also, the frequency of the current may be 5208 Hz, which corresponds to a period of 192 microseconds.

[0099] The magnetic field created by this device readily penetrates through the bone. In the context of TMS, where the magnetic field desirably stimulates the brain, but undesirably stimulates nerves, muscle and tissue proximate to the scalp, a three dimensional field analysis is illustrated in Figure 19. As shown in Figure 19, the electric field circulates around the magnetic field created by a magnetic core device 1901. Although the electric field created by magnetic core device 1901 is circular, the electric fields created by the conductors typically are not, except for the local fields produce by the conductors.

[0100] Figure 20 illustrates one possible placement of two conductors 2001 and 2002. Conductors 2001 and 2002 are shown located with respect to the magnetic core device 1901, but

it should be appreciated that the conductors may be located with reference to any object, including the patient's head, for example. In this particular example, a voltage of approximately 10 volts may be placed on conductor 2001 and a voltage of approximately -5 volts may be placed on electrode 2002.

[0101] The regions circumscribed by boxes 2003 and 2004 indicate areas where the fields created by conductors 2001 and 2002 effectively cancel or reduce the undesirable fields created by magnetic core device 1901. Also, the voltages applied to conductors 2001 and 2002 may be varied to achieve optimal cancellation or reduction of the fields in the desired regions. There also may be regions in which the fields are not optimally reduced or eliminated, such as the region circumscribed by box 2005.

[0102] In order to determine optimal conductor size, configuration and location, the electric field created by magnetic core device 1901, conductor 2001 and conductor 2002 may be considered at numerous specific points or locations and be analyzed accordingly. The electric field at any point on the surface from all three sources may be represented by the following equation:

$$\vec{E}_{total} = \left\{ E_z^{mag A} + V_A E_z^{elec A} - V_B E_z^{elec B} \right\} \hat{d}_z + \left\{ E_\phi^{mag A} + V_A E_\phi^{elec A} - V_B E_\phi^{elec B} \right\} \hat{d}_\phi. \quad (1)$$

Also, the sum of all the fields may be represented by the following equation:

$$\mathcal{F} = \sum_{all \ points} \sqrt{\left\{ E_z^{mag A} + V_A E_z^{elec A} - V_B E_z^{elec B} \right\}^2 + \left\{ E_\phi^{mag A} + V_A E_\phi^{elec A} - V_B E_\phi^{elec B} \right\}^2}. \quad (2)$$

[0103] $E^{mag A}$ represents the value of the electric field created by magnetic core device 1901 at a particular point. Similarly, $E^{elec A}$ and $E^{elec B}$ represent the values of the electric fields created by conductor 2001 and conductor 2002, respectively, at the same or similar particular point. Also, E_z represents the vertical electric field and E_ϕ represents the azimuthal fields. A computer simulation may be conducted to permit conductor 2001 and conductor 2002 to be varied in location, size and configuration to determine optimal field cancellation of the undesirable fields in the desired locations. For example, conductor 2001 and conductor 2002 may be allowed to move vertically, stretch out azimuthally, and have their dimensions adjusted, for example. Also, the equations may be used to determine the optimal voltages to apply to conductor 2001 (V_A) and to conductor 2002 (V_B).

[0104] Figure 21 illustrates an embodiment where just one pair of conductors 2101 and 2102 are used to reduce the fields created by magnetic core device 1901. Typically, one conductor pair may be used to reduce or diminish fields in the area in which the device creates

the strongest field concentration (*e.g.*, for magnetic core device 1901 along the axis of the core). The voltage across conductors 2101 and 2102 may be set at 3.83 volts and the conductors each may be approximately 1/8 inch thick. The excitation signal may be 20,364 Ampere-turns at 5.2 kilohertz. Conductor 2101 and conductor 2102 each are placed approximately 0.8 inches above and below the midline of magnetic core device 1901. A one-quarter section is cut from magnetic core device 1901 to aid in visibility.

[0105] Figure 22 graphically depicts the comparison of the electric field created by magnetic core device 1901 both with and without cancellation by the conductors 2101 and 2102. In particular, as shown in Figure 22, the presence of the conductor(s) fold the electric field pattern of magnetic core device 1901 along the core axis at $\Theta=0$, thus shifting it away from the axis. As a result, the peak field over the surface drops from 4.91 volts/centimeter without cancellation to approximately 4.46 volts/centimeter with cancellation.

[0106] Figure 23 illustrates an embodiment where six conductors 2301-2306 are used to reduce the fields created by magnetic core device 1901. In this particular example, the six conductors make two voltage pairs, with conductors 2301 and 2302 paired together, while conductors 2303-2306 are grouped together. As shown in Figure 23, conductors 2303-2306 each are approximately 1.5625 inches above and below the midline of magnetic core device 1901. Also, conductors 2301 and 2302 each are 0.8125 inches above and below the midline of magnetic core device 1901. The width of conductors 2301 and 2302 each may be 2.52 inches, while the width of conductors 2303-2306 each may be 1.17 inches. A voltage of 1.86 volts may be created between conductors 2301 and 2302, while a voltage of 3.37 volts may be created between any pair of conductors 2303-2306. In addition, conductors 2301-2306 may be 1/8 inch thick.

[0107] With the conductor configuration illustrated in Figure 23, the peak surface field of magnetic core device 1901 may be reduced from 4.91 volts/centimeter without the cancellation to 4.36 volts/centimeter with cancellation.

[0108] As discussed, the voltage waveform to the conductors should be timed with the generation of fields created by the stimulation device to maximize desirable cancellation. In particular, the voltage provided to the conductors may be timed with the current in the stimulation device. Figure 25 provides just one example embodiment of such a possible timing configuration. As shown in Figure 25, using a magnetic core device and stimulation circuit similar to that discussed with reference to Figures 19-24, for example, proper timing of the application of voltage signals to the conductors may be considered with respect to the TMS example discussed.

[0109] As previously discussed, voltage induced in the skin is proportional to the derivative of the magnetic field. Also, because conductivity of the stimulation device typically is relatively small, the derivative of the magnetic field created by the stimulation device is substantially similar to the derivative of the current provided to the stimulation device. In Figure 24, the top graph illustrates that the current for magnetic core device 1901 as a function of time is a decaying sinusoid. The lower graph illustrates the accompanying conductor potential necessary to realize the field cancellation and/or reduction. Although the current begins at current may begin a zero, the voltage on the electrode does not. Table I provides an example of the values of the conductor voltage in different configurations along with the core current. Notably, as the magnetic core excitation current scales, so must the conductor voltage also scale.

Table I Current and Electrode Voltage versus Time

Time(μ s)	Current (A)	One Conductor Pair (V)	Two Pair A (V)	Two Pair B (V)
5	620	5.289	2.568	4.654
10	1100	5.334	2.590	4.693
15	1620	5.416	2.630	4.766
20	2100	5.406	2.625	4.757
25	2740	4.961	2.409	4.365
30	3100	3.982	1.934	3.504
35	3580	2.516	1.222	2.214
40	3620	0.858	0.417	0.755
45	3660	-0.590	-0.286	-0.519
50	3500	-1.749	-0.849	-1.539
55	3260	-2.589	-1.258	-2.278
60	3020	-3.307	-1.606	-2.909
65	2700	-4.011	-1.948	-3.529
70	2220	-4.508	-2.189	-3.967
75	1740	-4.666	-2.266	-4.105
80	1300	-4.640	-2.254	-4.083
85	860	-4.619	-2.243	-4.064
90	420	-4.677	-2.271	-4.115
95	0	-4.788	-2.325	-4.213
100	-560	-4.715	-2.290	-4.148

105	-1040	-4.373	-2.124	-3.848
110	-1320	-4.097	-1.990	-3.605
115	-1800	-3.869	-1.879	-3.404
120	-2080	-3.515	-1.707	-3.093
125	-2520	-2.873	-1.395	-2.528
130	-2720	-1.908	-0.927	-1.679
135	-2840	-0.883	-0.429	-0.777
145	-2840	1.082	0.526	0.952
150	-2640	1.879	0.912	1.653
155	-2440	2.470	1.200	2.174
160	-2240	2.991	1.452	2.632
165	-1800	3.290	1.598	2.894
170	-1560	3.418	1.660	3.008
175	-1200	3.561	1.729	3.133
180	-920	3.655	1.775	3.216
185	-480	3.439	1.670	3.026
190	-160	2.690	1.306	2.367
195	100	1.532	0.744	1.348
200	220	0.310	0.150	0.273
205	0	-0.358	-0.174	-0.315
210	0	-0.463	-0.225	-0.408

[0110] It is to be understood that the foregoing illustrative embodiments have been provided merely for the purpose of explanation and are in no way to be construed as limiting of the invention. Words used herein are words of description and illustration, rather than words of limitation. In addition, the advantages and objectives described herein may not be realized by each and every embodiment practicing the present invention. Further, although the invention has been described herein with reference to particular structure, materials and/or embodiments, the invention is not intended to be limited to the particulars disclosed herein. Rather, the invention extends to all functionally equivalent structures, methods and uses, such as are within the scope of the appended claims. Those skilled in the art, having the benefit of the teachings of this specification, may affect numerous modifications thereto and changes may be made without departing from the scope and spirit of the invention.